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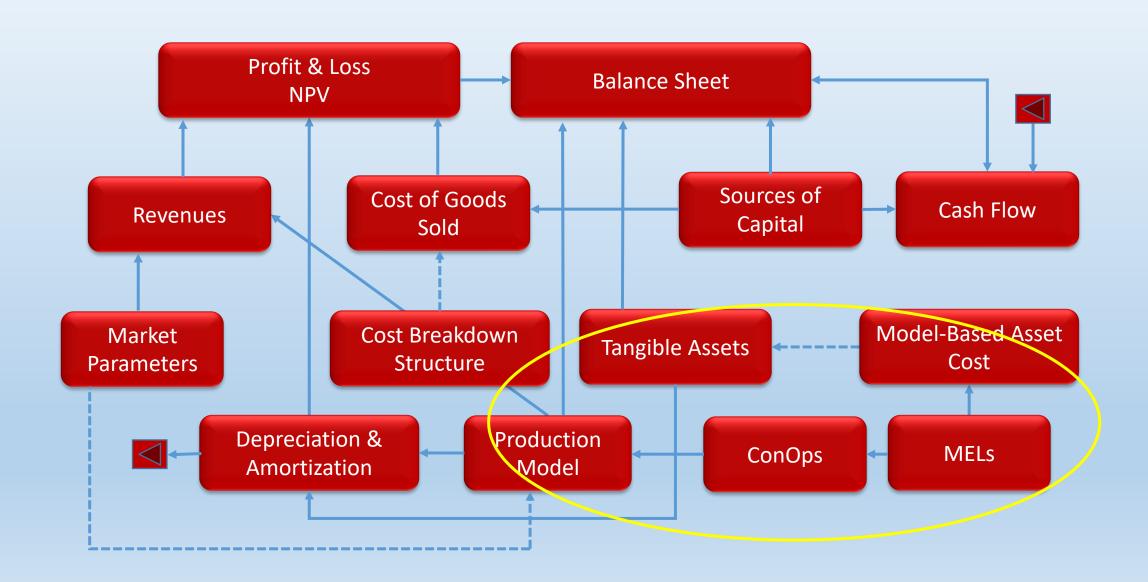
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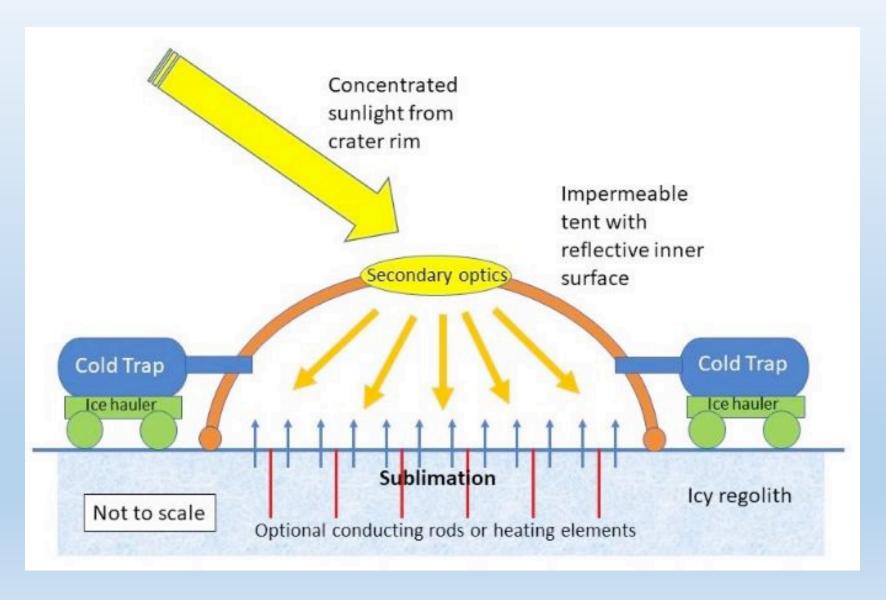
Purpose

- Establish the case for the proposed ISRU technology against delivering propellant from Earth (or other alternative).
 - Establish at what level of demand, if any, does the business case close.
 - Determine if and where tipping points occur.
- Develop an engineering-based production rate model for the proposed ISRU technology that enables tradespace exploration.
 - Provide quantitative estimates for design parameters (e.g., element mass).
 - Determine which design parameters in the design vector have the greatest effect on production?
 - Determine which feasible combinations of those design parameters make the most sense?

Establishing the Business Case: Lean BCA Framework



Lunar Thermal Mining Concept



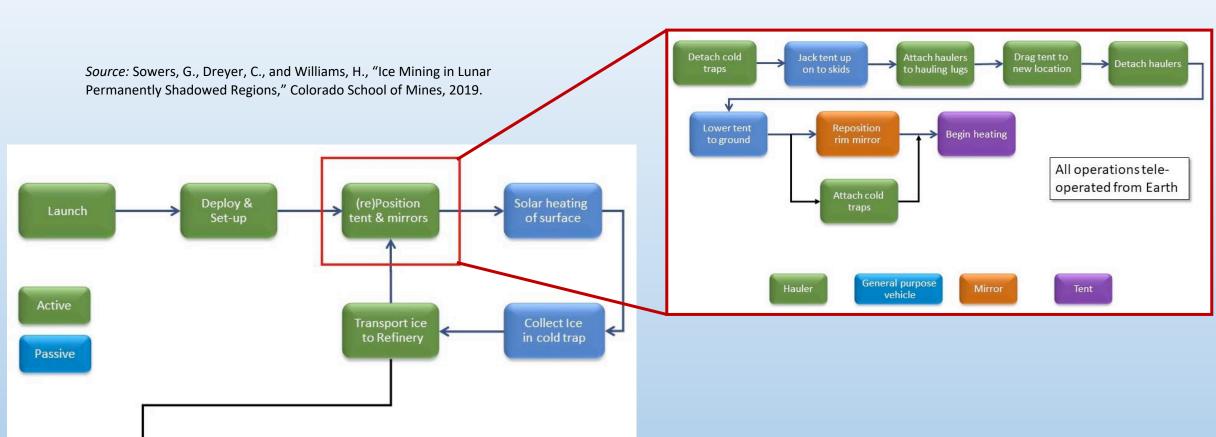
Lunar Thermal Mining Concept of Operations

Propellant

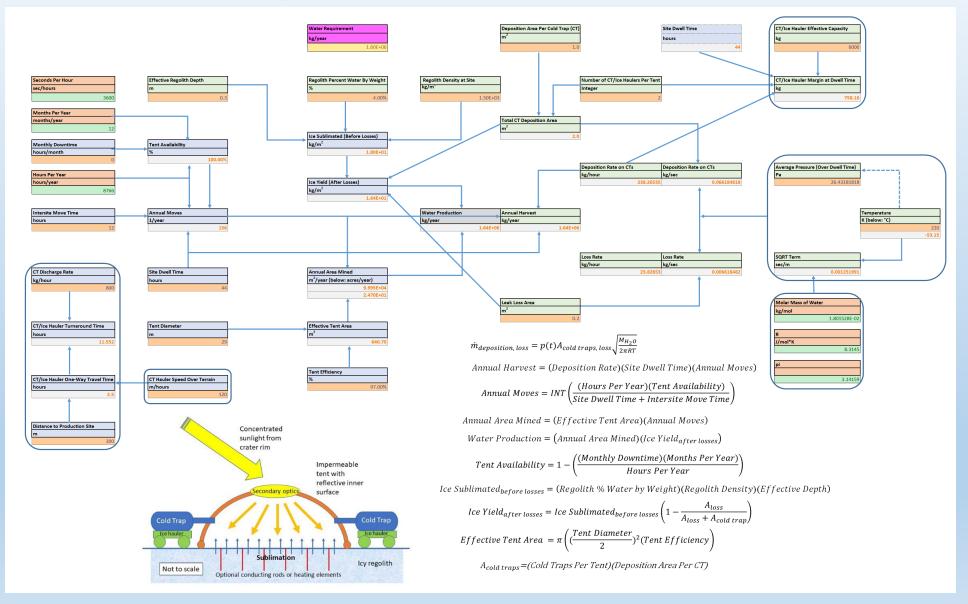
Storage & Handling

Electrolysis

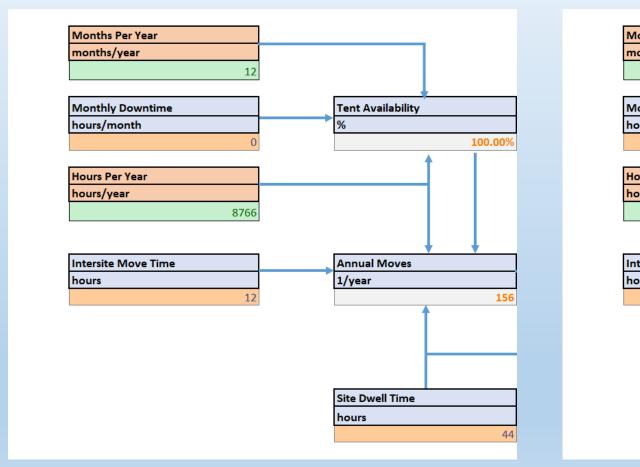
Purify ice /

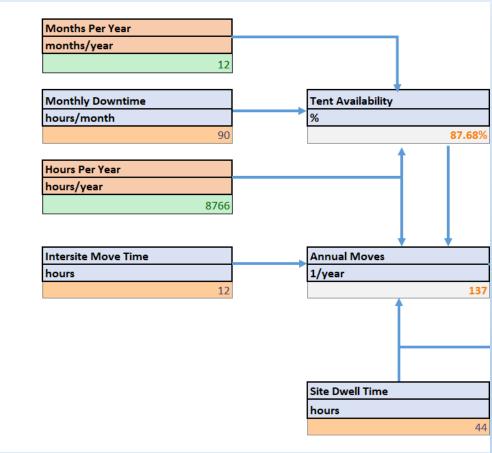


Lunar Thermal Mining Production Model: "Threads of Calculation"

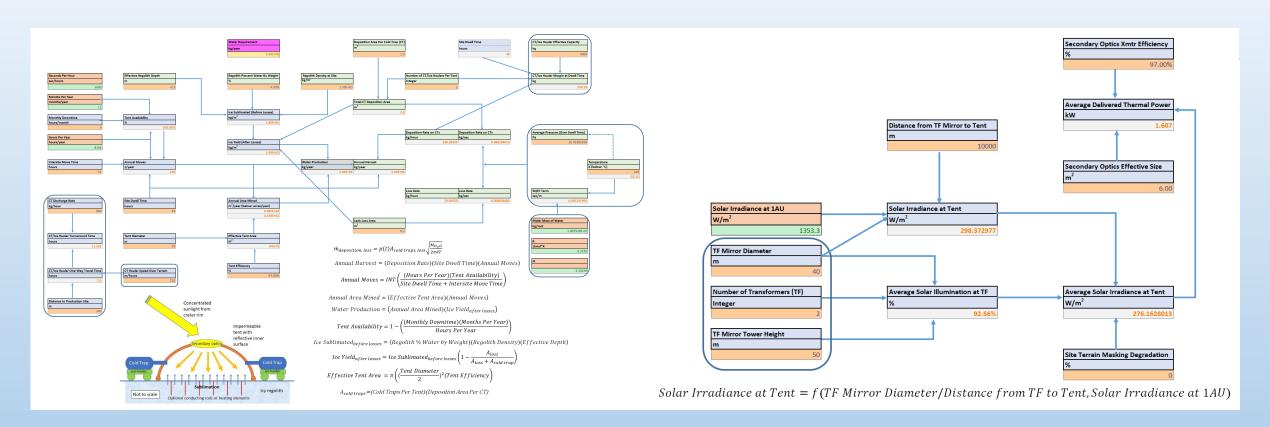


"Threads of Calculation" from Tent Downtime to Annual Tent Moves and Annual Production





Lunar Thermal Mining Production Model: "Threads of Calculation"

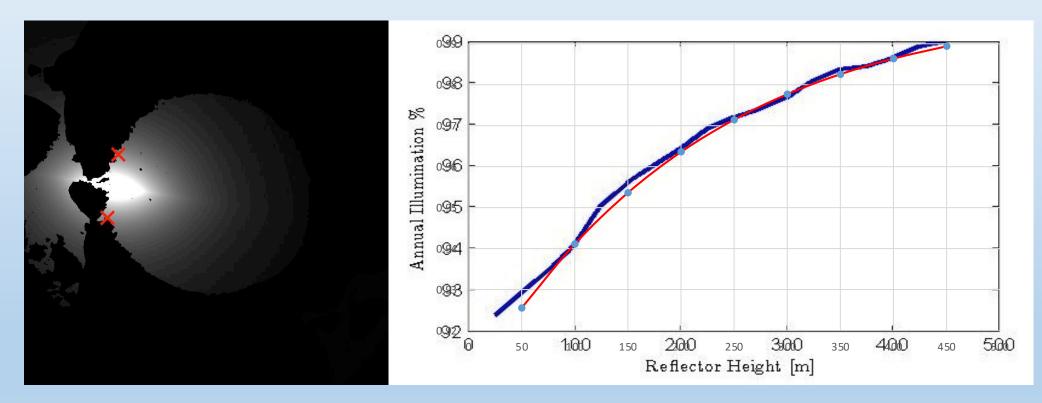


In total so far, the design vector has 22 input variables, excluding physical constants.

Average Solar Illumination

Source: Henrickson, J., Stoica, A., "Reflector Placement for Providing Near-Continuous Solar Power to Robots in Shackleton Crater," IEEE Aerospace Conference, Big Sky, MT, 2017.

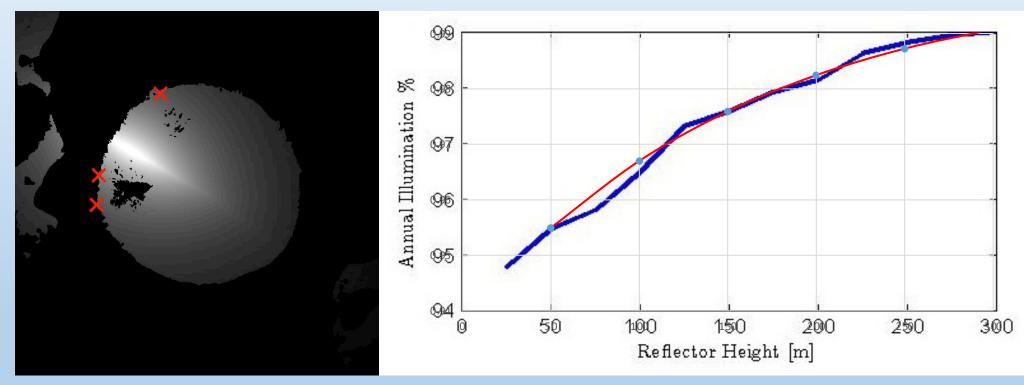
Results for Two TransFormers Located at 89.9029°S 145.2301°W and 89.6876°S 162.8645°W



L = exp(2.26844 + 0.00504H)/(1 + exp(2.26844 + 0.00504H))

Average Solar Illumination

Source: Henrickson, J., Stoica, A., "Reflector Placement for Providing Near-Continuous Solar Power to Robots in Shackleton Crater," IEEE Aerospace Conference, Big Sky, MT, 2017. Results for Three TransFormers Located at 89.8172°S 153.5004°W, 89.8262°S 52.8422°E, and 89.6876°S 162.8645°W



L = exp(2.729668 + 0.00648656H)/(1 + exp(2.729668 + 0.00648656H))

Production Model Engineering Database

Maintains configuration management for tradespace exploration input and output data

Scenario	rio Equipment			Parameter		Parameter	Parameter
ID	→ ID		Equipment Name	ID ,T	Parameter Name	Units	Value -
	1	1	Thermal Tent Mobility/Setup Robotics	3	Monthly Downtime	hours	5
	1	1	Thermal Tent Mobility/Setup Robotics	4	Design Life	years	10
	1	1	Thermal Tent Mobility/Setup Robotics	12	Unit Dry Mass	kg	1000
	1	2	Cold Trap/Ice Hauler	3	Monthly Downtime	hours	
	1	2	Cold Trap/Ice Hauler	4	Design Life	years	10
	1	2	Cold Trap/Ice Hauler	5	Effective Capacity	kg	6000
	1	2	Cold Trap/Ice Hauler	6	Distance (Excavation Site-to-Plant)	m	300
	1	2	Cold Trap/Ice Hauler	12	Unit Dry Mass	kg	1050
	1	2	Cold Trap/Ice Hauler	18	Effective Speed Over Terrain	m/hour	180
	1	3	Solar Reflectors (TransFormers)	2	Height	m	50
	1	3	Solar Reflectors (TransFormers)	8	Diameter	m	40
	1	3	Solar Reflectors (TransFormers)	9	Efficiency	%	96
	1	4	ISRU Water Purification and H2-O2 Production	3	Monthly Downtime	hours	
	1	4	ISRU Water Purification and H2-O2 Production	4	Design Life	years	10
	1	4	ISRU Water Purification and H2-O2 Production	10	Nominal Production Rate	mt/year	
	1	4	ISRU Water Purification and H2-O2 Production	12	Unit Dry Mass	kg	3000
	1	5	Liquefaction Unit	3	Monthly Downtime	hours	
	1	5	Liquefaction Unit	4	Design Life	years	8
	1	5	Liquefaction Unit	10	Nominal Production Rate	mt/year	
	1	5	Liquefaction Unit	12	Unit Dry Mass	kg	3000
	1	6	Integrated Cryo-Propellant Hauler w/CFM	3	Monthly Downtime	hours	
	1	6	Integrated Cryo-Propellant Hauler w/CFM	4	Design Life	years	10
	1	6	Integrated Cryo-Propellant Hauler w/CFM	5	Effective Capacity	kg	
	1	6	Integrated Cryo-Propellant Hauler w/CFM	7	Distance (Plant-to-Lander Site)	m	1000
	1	6	Integrated Cryo-Propellant Hauler w/CFM	12	Unit Dry Mass	kg	1000
	1	6	Integrated Cryo-Propellant Hauler w/CFM	18	Effective Speed Over Terrain	m/hour	180
	1	7	Thermal Tent w/Secondary Optics	8	Diameter	m	29
	1	7	Thermal Tent w/Secondary Optics	9	Efficiency	%	0.97
	1	7	Thermal Tent w/Secondary Optics	11	Move and Set-Up Time	hours	12
	1		Thermal Tent w/Secondary Optics	12	Unit Dry Mass	kg	8000
	1		Power Generation Station	3	Monthly Downtime	hours	
	1	8	Power Generation Station		Design Life	years	15
	1	8	Power Generation Station	12	Unit Dry Mass	kg	4000
	1	8	Power Generation Station	16	Power	W	

Lunar Thermal Mining In-Service Elements

Scenario	Equipment		Equipment	Required Operational	Required Spares
ID	ID	Equipment Name	Operating Location	Quantity	Quantity
1	1	Thermal Tent Mobility/Setup Robotics	PSR	4	1
1	2	Cold Trap/Ice Hauler	PSR	2	1
1	3	Solar Reflectors (TransFormers)	Crater Rim	3	0
1	4	ISRU Water Purification and H2-O2 Production	PSR	2	0
1	5	Liquefaction Unit	PSR	1	0
1	6	Integrated Cryo-Propellant Hauler w/CFM	PSR	2	0
1	7	Thermal Tent w/Secondary Optics	PSR	1	0
1	8	Power Generation Station	PSR	1	0

Depreciation & Amortization

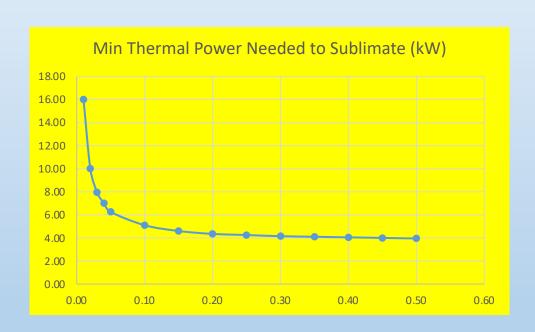
Tangible Assets Attributes

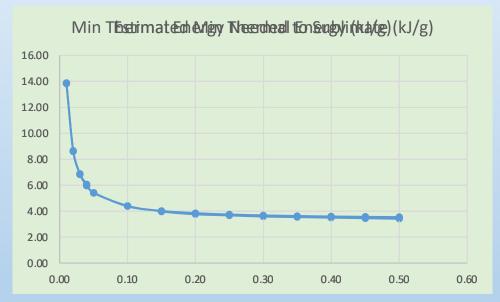
- Contains development and TFU estimated cost, acquisition time, dry mass, volume, power, data rate, capacity, availability, design life (replacement time), cost margin to be applied.
- Calculates year-by-year costs.
- Development and TFU cost CT/Ice Hauler from Quickcost v.6.0, released March 2016
 - 1.05 mt dry mass
 - 50% new design



Thermal Power Needed to Sublimate 100 kg/day Versus Percent Water in Icy Regolith

Source: Stoica, A., et al., "TransFormers for Extreme Environments: Ensuring Long-Term Operations in Regions of Darkness and Low Temperatures," NIAC Phase II Final Report, November 2017.





$$P = 3.312084 + 0.1056103$$
 coth w

Results Recapitulation

- An engineering-based production rate model is essential to build a defensible BCA.
- Progress in creating a thermal mining production rate model as a function of the "assets" (elements) to be deployed and employed on the lunar surface.
 - Reliability and maintainability considerations (MTBF and MTTR) are important in estimating the overall production rate and the number of "stand-by" assets needed.
 - Other logistics considerations regarding robotic travel distances and speed over terrain could add waiting time, thereby decreasing the overall production tempo.
 - To be consistent, the CT/Ice Hauler dry mass needed to be ~15% 30% larger than previously published.
 - Location (e.g., %water by weight) and element position geometry matter (e.g., solar thermal power delivered within tent depends strongly on the distance from the crater rim-sited solar reflectors and the tent, and on reflector diameter and height above terrain.)
- Estimating the costs of each element will be a continuing challenge.
 - Current cost models for spacecraft may not be appropriate for surface systems

Moving Forward

- Relationship between the thermodynamic properties of regolith/lunar ice and the ice deposition rate (via tent pressure build-up) not yet established.
 - Not a clear relationship yet between solar thermal power delivered and tent pressure buildup as a function of percent water by weight and other tent physical parameters.
 - Thermal diffusivity of regolith at PSR conditions.*
 - Sublimation, vapor transport, and deposition processes and rates.*
 - Effects of ice grain size, porosity, and impurities.*
- Need actual lunar demonstrations informed by laboratory simulations
- Need more detail in the ops concept in order to validate production rate model.
- Need to incorporate uncertainty.

References

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- 8. Frias, J., Shafirovich, E., and Van Woerkom, M., "Extraction of Volatiles from Lunar Regolith Using Solar Power," J. Thermophysics and Heat Transfer, Vol.28, No. 2, April June 2014.
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Backup

Business Case Analysis of Lunar Thermal Mining

Establishing the Business Case: The Lean Framework Implemented

- Sheet Name: System MEL (1 Sheet Per System)
 Contains the mass of spacecraft and surface systems, and the ConOps for their employment.
- Sheet Name: Launch Vehicles and Costs Contains LV performance and costs.
- Sheet Name: Detailed In-Service Schedule
 Contains the number of assets placed in service quarterly. Also contains
 quarterly costs associated with launch services. Use of this detailed sheet is
 optional, if the user wants to provide placed-in-service on a year-by-year
 basis directly on the depreciation sheet.
- Sheet Name: Cost Breakdown Structure
 Sets the high-level cost structure used in the COGS sheet.
- Sheet Name: Schedule and Activity Cost
 Provides detailed accounting of all costs. Nominally, the quarterly costs
 entered on this sheet are aggregated to annual costs on the COGS sheet. Use
 of this detailed sheet is optional, if the user wants to provide costs on a year by-year basis directly on the COGS sheet.
- Sheet Name: Cost of Goods Sold (COGS)
 Contains all costs against each cost breakdown structure element.
- Sheet Name: Tangible Assets
 Contains the list of all assets with asset characteristics such as development
 and production costs, development and production durations, replacement
 schedules, type of depreciation, buy-or-lease, etc. Also spreads development
 and production costs across multiple years according to asset characteristics
 specified by the user.

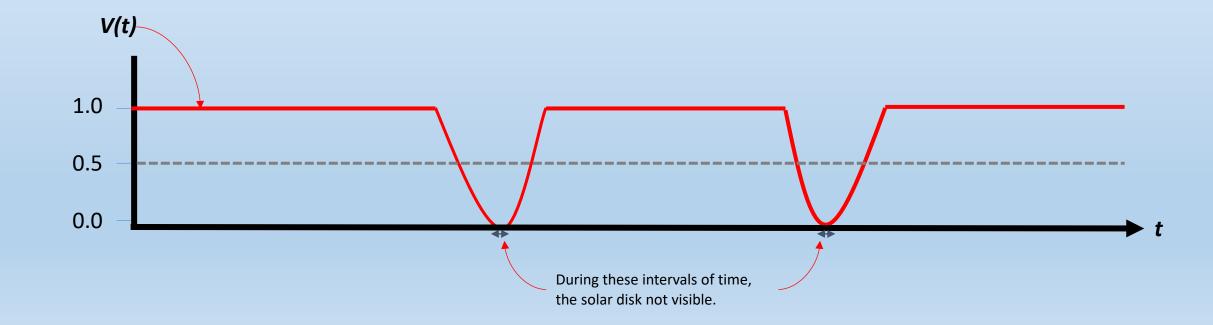
- Sheet Name: Depreciation
 Computes depreciation (and amortization) based on tangible asset
 characteristics and the number of each asset place in service each year.
 Depreciation (straight-line or accelerated) is computed using VBA code.
- Sheet Name: Thermal Mining Production Model Determines how many mining surface systems, $k_1, k_2, \ldots k_n$, are needed to satisfy annual customer demands.
- Sheet Name: Power and Illumination Model Determines how many power surface systems, k_{n+1} , k_{n+2} , . . . k_{n+m} , are needed to satisfy annual customer demands.
- Sheet Name: Detailed Revenue Forecast
 Contains a detailed (by quarter) revenue (sales) forecast. Use of this detailed
 sheet is optional, if the user wants to provide revenues on a year-by-year
 basis directly on the sales sheet.
- Sheet Name: Sales
 Aggregates all sales/revenues, computed from quantity sold and sales price for each revenue stream. Allows price to change from year-to-year.
- Sheet Name: Cash Flow Computes cash flow and accounts for all sources of capital.
- Sheet Name: Balance Sheet
 Aggregates total assets and liabilities and computes total equity.
- Sheet Name: Profit and Loss
 Aggregates revenues and costs, depreciation and taxes to get net profit. Also
 computes NPV and IRR when feasible.

Definition: Average Solar Illumination

$$\overline{S_{\theta}} = \left(\frac{1}{T_2 - T_1}\right) \int_{t = T_1}^{t = T_2} V(t; \theta) dt \text{ where } V(t; \theta) = \begin{cases} V(t), & 1 \ge V(t) \ge \theta \\ 0, & otherwise \end{cases}$$

Note 1: V is the fraction of the solar disk that is visible at a specific location on the lunar surface. Θ is the fraction of the solar disk visibility above which the visibility is to be included in the average, so $\overline{S_0}$ averages V(t) over the full time domain. Similarly, $\overline{S_1}$ counts V(t) only when the full solar disk is visible.

Note 2: Usually, the average is taken over a calendar year or a longer multiyear period.



Definition: Average Solar Visibility

$$\overline{V_{\theta}} = \left(\frac{1}{T_2 - T_1}\right) \int_{t = T_1}^{t = T_2} V(t; \theta) dt \text{ where } V(t; \theta) = \begin{cases} 1, & 1 \ge V(t) \ge \theta \\ 0, & otherwise \end{cases}$$

Note 1: V is the fraction of the solar disk that is visible at a specific location on the lunar surface. Θ is the fraction of the solar disk visibility above which the visibility is to be included in the average, so $\overline{V_0}$ is the fraction of time any solar light is visible. Similarly, $\overline{V_1}$ is the fraction of time the full solar disk is visible.

Note 2: Usually, the average is taken over a calendar year or a longer multiyear period.

Note 3: Average Solar Visibility ≥ Average Solar Illumination.

